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Critical magnetic field in regularly nanostructured indium

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Introduction

The behaviour of nanostructured superconductors, being well documented in 2-dimensional case, is far less studied for 3D regular arrays of superconductor nanostructures because it is much more difficult to prepare the high-quality 3D lattices. To achieve the uniformity of intergrain contacts and the crystalline quality of the array we applied the template method, which is based on the impregnation of the crystalline porous dielectric matrix with the metal. The aim of this report is to discuss the critical magnetic field of the indium-opal nanocomposite.

1. Materials and measurement techniques

Opals consist of identical silica balls assembled in face centred cubic (fcc) lattice. There are alternated voids in opal: O-voids ($d_O = 0.41D$, $D = 234$ nm — ball diameter in the sample) each connected with eight T-voids ($d_T = 0.23D$ via channels of characteristic diameter $d_b = 0.15D$ [1]. In order to reduce the free volume the opal was impregnated with amorphous silica. Further reduction of porosity was achieved by coating the opal voids with 34 monolayers of TiO_2. Effectively, the overall reduction of the void size was about two times as compared with ideal package for the same lattice parameter. Impregnation with molten In has been performed and metal forms the precise 3D replica formation of opal voids [2]. Detailed investigation of the composition of In-opal structures is given elsewhere [3].

2. Experimental results and discussion

The $R(T)$ curve (Fig. 1(a)) shows a peak at $T = 4.24$ K followed by the broadened decline of resistance to 0 at $T_{c0} = 3.7$ K. The critical temperature of superconducting (SC) transition T_c exceeds sufficiently that of the bulk indium (3.41 K). The $R(T)$ curve shows three steps, temperatures of which correspond to maxima of the dR/dT curve (Fig. 1(b)).

The SC transition is spread broadly by a field (Fig. 2) and demonstrates several steps: H_0 as the critical magnetic field of transition from the SC to the resistive state, H_1 and H_2 — characteristic fields for steps. Remarkably, the H_0 field exceeds dramatically the critical field for the bulk In (280 Oe at $T = 0$). Temperature dependences of H_1 and H_2 show nearly the same slope as $H_0(T)$, moreover the field values follow roughly the 1:2:3 sequence.

Confining the SC condensate in nanostructures with characteristic dimension $d < \xi_{bulk}$ implies the involvement of the whole volume of grains in the supercurrent transfer. Obviously, the increase of the T_c above the bulk value correlates with the reduced dimensionality of the In network. The presence of different parts possessing the well-defined dimensions is reflected by the steps on $R(T)$ curve. Assuming that the SC nucleates at the narrowest part, the onset of the resistance drop corresponds to the SC transition in intergrain bridges.

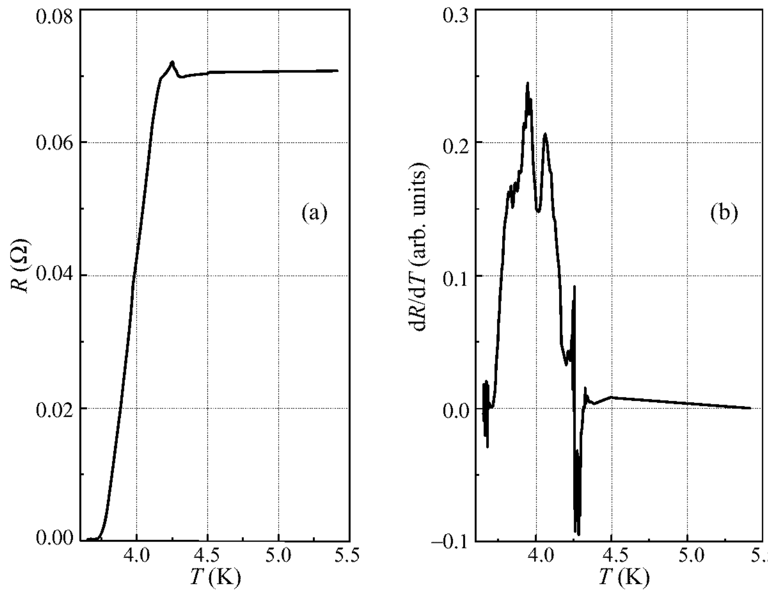

Fig. 1. (a) resistance vs temperature dependence of the In-opal; (b) temperature derivative of the resistance $\mathrm{d}R/\mathrm{d}T$.

The empirical expression $T_c = 3.41 + 5.1/d$ [d in nm] [4] gives the d estimate as 7 nm, which is the bridge diameter.

In In-opal every current path consists of symmetrical arms, moreover both arms joined and separated in periodical manner. In other words, the current encircles the loop circumferences. The Ginsburg–Landau estimate for the lower critical field of the mesoscopic loop varies between $\mu(0)H_{c1}^{\text{loop}} = \Phi_0/(2\pi r^2)$, where $r = \sqrt{(r_{\text{out}} r_{\text{in}})}$ is the average between inner and outer ring radii, for the ring with $r_{\text{out}} - r_{\text{in}} \ll r$ and up to 4 times higher value for $r_{\text{out}} - r_{\text{in}} \leq r$ [5]. The projection of the smallest loop to (111) plane is about $2r = 2D/\sqrt{6} = 98$ nm, correspondingly, the $H_{c1}^{\text{loop}} = 1.4{-}5.5$ kOe applies. This estimate matches the critical fields observed in In-opal. In contrast, if one accounts for the size-dependent enhancement of the critical magnetic field only $H_c^{\text{d}}(T)/H_c^{\text{bulk}}(T) = 4\sqrt{5}\lambda(T)/d$, where $\lambda(T) = \lambda(0)(1 - (T/T_c)^4)^{-0.5}$, $\lambda(0)$ — the penetration depth in the bulk superconductor, the particle size d has to be less than 5 nm.

In a loop with a fixed circumference the screening supercurrent must flow to fulfil the fluxoid quantization conditions if the external field corresponds to the non-integer number of flux quanta per loop. These currents can be described in the same manner as magnetic vortices. In the loop lattice there is the possibility of mutual cancellation of screening currents in common arms of adjacent loops, i.e. the actual distribution of the current depends on the lattice symmetry. Magnetic field penetrates deeply $\Lambda = \lambda^2(T)/d$ in the nanostructured sample, i.e. the field around the single vortex is weakly screened and the repulsive interaction is of longer range as compared with the type II superconductor. Thus, loops within the cluster of ξ, Λ dimensions are strongly coupled. Correspondingly, the behaviour of the lattice as the whole is definitely different from that of a collection of loops with the smallest areas. Due to these complications the observed characteristics deviate sufficiently from estimates made for the single loops and grains.

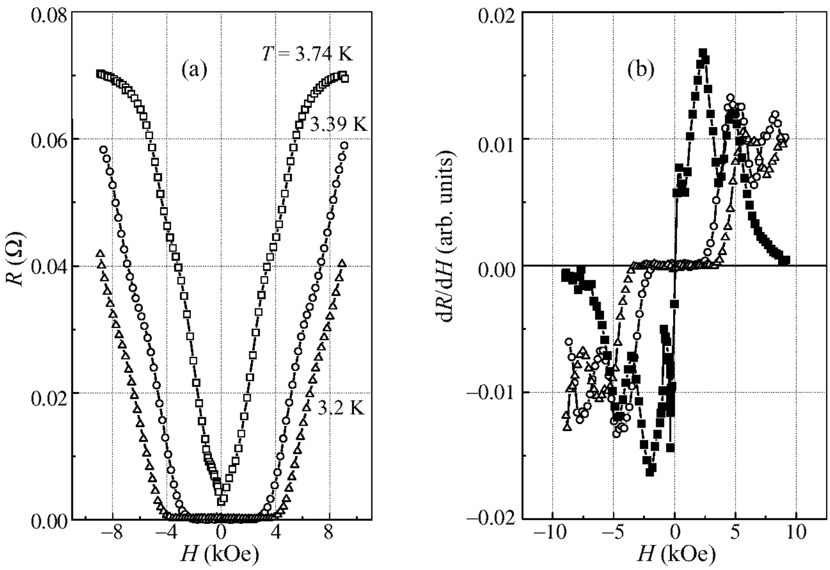

Fig. 2. (a) Magnetoresistance curves $R(H)$ for different temperatures; (b) magnetic field derivative of the resistance $\mathrm{d}R/\mathrm{d}H$.

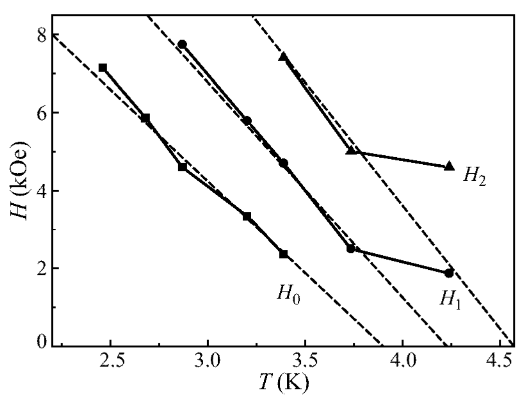

Fig. 3. Temperature dependences of the characteristic fields H_0 (the beginning of the SC transition), H_1 and H_2 (correspond to the steps on the $R(H)$ dependences).

Let us suppose that the critical field is the field when each loop has caught one flux line. At higher field the transport plus screening current exceeds the critical current of the intergrain bridge. In this case the connectivity changes from multiply connected to single connected and a flux line can move easily in and out the loop. This state of the network is obviously the resistive state because the dissipative motion of flux lines across the field/current direction causes the voltage $V \propto (H - H_0)$ and the onset of the magnetoresistance. With further increase of the field it becomes energetically favourable to add the second quantum in each loop. This field H_1 is roughly twice as H_0. The next kink can be assigned to the accumulation of the third flux quantum per each loop, because its field $H_2 \approx 3H_0$. With the use of the expression for the flux quantization and value for $\Delta H = 2.7$ kOe one can estimate the effective loop diameter as 88 nm, which is appealingly

close to the size of the smallest loop in the lattice.

3. Conclusions

The giant increase of the critical magnetic field was observed in the regular lattice of nanosize In loops. Two effects — the reduction of the loop arm cross-section and the regularity of the ensemble, are believed to contribute mainly to the observed effect.

Acknowledgements

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